

An alternate spintronic analog of the electro-optic modulator

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There is significant current interest in spintronic devices fashioned after a spin analog of the electro-optic modulator proposed by Datta and Das [Appl. Phys. Lett., 56, 665 (1990)]. In their modulator, the “modulation” of the spin polarized current is carried out by tuning the Rashba spin-orbit interaction with a gate voltage. Here, we propose an analogous modulator where the modulation is carried out by tuning the Dresselhaus spin orbit interaction instead. The advantage of the latter is that there is no magnetic field in the channel unlike in the case of the Datta-Das device. This can considerably enhance modulator performance.

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In 1990, Datta and Das proposed a spintronic analog of the electro-optic modulator [1]. It consists of a quasi one-dimensional semiconductor channel with ferromagnetic source and drain contacts (Fig. 1(a)). Electrons are injected with a definite spin orientation from the source, which is then controllably precessed in the channel with a gate-controlled Rashba spin-orbit interaction [2], and finally sensed at the drain. At the drain end, the electron's transmission probability depends on the relative alignment of its spin with the drain's (fixed) magnetization. By controlling the angle of spin precession in the channel with a gate voltage, one can control the relative spin alignment at the drain end, and hence control the source-to-drain current. This realizes the basic “transistor” action. Because of this attribute, the Datta-Das device came to be known as the ballistic Spin Field Effect Transistor (SPINFET).

Despite the fact that the SPINFET was proposed more than a decade ago, it has never been experimentally realized. Recently, we found that one of the serious impediments to its realization is the presence of a magnetic field in its channel caused by the ferromagnetic source and drain contacts. This field has been ignored in practically all past work, but has crucial consequences. Based on available data for device configurations that are similar to the SPINFET [3], we estimate that in a $0.2\ \mu\text{m}$ long channel, the average magnetic field may approach 1 Tesla. This field has many deleterious effects [4, 5]. First, it results in a Zeeman spin splitting that affects the dispersion relations of the Rashba spin split subbands in the channel. Consequently, there is “spin mixing” in each subband, so that no subband has a definite spin quantization axis [4]. As a result, non-magnetic scatterers can flip spin [5] thereby making spin transport non-ballistic in the presence of normal impurities, surface roughness, etc., which otherwise would not have affected spin transport. Second, the “phase shift” of the spintronic modulator will be no longer independent of energy [4, 5] (in ref. 1, it was claimed to be independent of energy because the channel magnetic field was ignored). Therefore, ensemble averaging over electron energy will dilute the modulation effect. Suffice it to say then that it is important to eliminate the magnetic field in the channel.

Although it is possible to engineer the Datta-Das device to reduce the channel field, it

can never be completely eliminated (unless complicated spin filter devices [6] are employed) since the magnetization in the source and drain contacts have to be always *along* the channel. The only other solution is to find an alternate analogous device where the magnetic fields due to the source and drain contacts are *transverse* to the channel. Here, we do precisely that and propose an alternate device, based on the Dresselhaus spin orbit interaction [7] rather than the Rashba interaction. In this device, the source/drain magnetization will be *transverse* to the channel, which vastly reduces the channel magnetic field. The only channel field that could be present is the fringing field at the edges adjoining the source and drain contacts. This is negligible.

Our device is schematically shown in Fig 1(b) and 1(c). Since it has no *structural* inversion asymmetry, we can ignore the Rashba interaction. However, there is a bulk inversion asymmetry in the channel material that ensures the presence of a Dresselhaus interaction. We will also assume a strictly one-dimensional (1-d) channel (only the lowest subband is occupied by carriers) in order to extract the best device performance. The need for one dimensionality was already elucidated in ref. 1. Furthermore, since there is no Dyakonov-Perel' spin relaxation in a strictly 1-d channel *in the absence of a channel magnetic field* [8], we can expect nearly ballistic spin transport. Following usual procedure, the 1-d channel will be defined by split gates [9] on the surface of a quantum well heterostructure.

The single-particle Hamiltonian describing an electron in the 1-d channel of this device is

$$H = \epsilon + \frac{\hbar^2 k_x^2}{2m^*} + 2a_{42}\sigma_x k_x \left[\frac{m^*\omega}{2\hbar} - \left(\frac{\pi}{W_y} \right)^2 \right] \quad (1)$$

where ϵ is the lowest subband energy, a_{42} is the material constant associated with the strength of the Dresselhaus interaction [10], σ is the Pauli spin matrix, and W_y is the channel dimension in the y-direction. We assume the potential profile in the y-direction to be a square well with hardwall boundaries and the potential profile in the z-direction is parabolic since confinement in this direction is enforced by split gates. The curvature of the parabolic potential is ω which can be tuned by varying the applied voltage on the Schottky split gates.

Here, we have assumed a direct gap semiconductor. The Dresselhaus spin orbit interaction term has a subtle dependence on the crystallographic orientation of the channel [11], but it is not *qualitatively* important in the present context. It may however assume importance in device optimization.

The rest of the analysis is fashioned after ref. 1. Diagonalizing the Hamiltonian in Equation (1), we find that the eigenspinors in the channel are $[1 \ 1]^\dagger$ and $[1 \ -1]^\dagger$ which are +x-polarized and -x-polarized states. They have eigenenergies that differ by $2\beta k_x$ where $\beta = 2 a_{42}[m^*\omega/(2\hbar) - (\pi/W_y)^2]$. Accordingly,

$$\begin{aligned} E(+x \text{ pol.}) &= \epsilon + \hbar^2 k_{x+}^2 / 2m^* + \beta k_{x+} \\ E(-x \text{ pol.}) &= \epsilon + \hbar^2 k_{x-}^2 / 2m^* - \beta k_{x-} \end{aligned} \quad (2)$$

An electron incident on the channel with energy E will have two different wavevectors k_{x+} or k_{x-} depending on whether its spin is +x or -x-polarized. Now, if we inject a +z-polarized electron into the channel from the source contact, it will couple equally to the +x and -x-polarized subbands since

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} 1 \\ -1 \end{bmatrix} \quad (3)$$

At the drain end, the eigenspinor will be $[e^{ik_{x+}L} + e^{ik_{x-}L} \ e^{ik_{x+}L} - e^{ik_{x-}L}]^\dagger$, where L is the channel length. If the drain is magnetized in the +z direction, then the transmission probability (and therefore the source to drain current) will be proportional to $|[1 \ 0][e^{ik_{x+}L} + e^{ik_{x-}L} \ e^{ik_{x+}L} - e^{ik_{x-}L}]^\dagger|^2 = 4 \cos^2[(k_{x-} - k_{x+})L/2] = 4 \cos^2[m^* \beta L / \hbar^2]$, where we have used Equation (2) to arrive at the last equality.

It is obvious now that this device is an exact analog of the device in ref. 1. As in ref. 1, we point out that the phase shift between the two orthogonal spin states (+x and -x polarized) is $\Delta\phi (= 2m^* \beta L / \hbar^2)$ which is independent of the electron wavevector (or energy). Therefore the interference between the two spin states causing the conductance modulation survives ensemble averaging over the electron energy at elevated temperatures. Actually, this is only

strictly true if there is no channel magnetic field [4, 5]. In the Datta-Das device, this would *not* have been strictly true because of the channel magnetic field, but in our case, it is.

The crucial difference between this device and that in ref. 1 is that here the contacts have to be magnetized in the z-direction so that the magnetic field caused by the contacts is *perpendicular* to the channel which is in the x-direction. That is why, we can neglect any Zeeman spin splitting in the channel which we could not do for the device in ref. 1. As mentioned before, this Zeeman spin splitting (or the channel magnetic field) would have been harmful to the device in many ways.

Before concluding, we can compare the minimum channel lengths L_{min} required to cause a phase shift of π radians between the two spin states. The channel must be at least this long in order to observe one complete cycle of switching from the maximum to the minimum conductance state. Comparing the two devices:

$$\frac{L_{min}|ref. 1}{L_{min}|this device} = \frac{\beta}{\eta} \approx \frac{a_{42}m^*\omega/(2\hbar)}{a_{46}\mathcal{E}} \quad (4)$$

where η is the strength of Rashba coupling as defined in ref. 1, a_{46} is a material parameter indicative of the degree of Rashba coupling and \mathcal{E} is the interface electric field causing the Rashba coupling. In GaAs, a_{42} is calculated to be 2.9×10^{-29} eV-m³ [10], a_{46} is calculated as 9×10^{-39} C-m² [12], and \mathcal{E} can be as high as 300 kV/cm. We will assume that $\hbar\omega = 25$ meV ($\hbar\omega \approx 25$ meV was achieved in ref. [9]). Based on these figures, $L_{min}|this device = 0.36L_{min}|ref. 1$, so that the two lengths are comparable (of the same order).

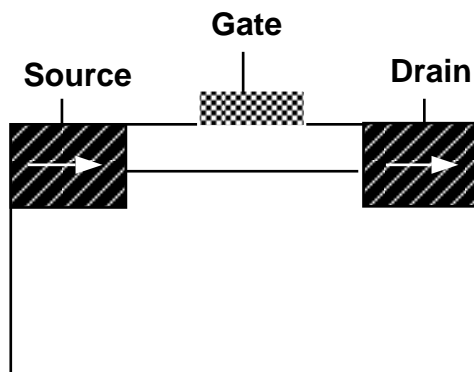
In conclusion, we have proposed a device which is analogous to the spintronic modulator proposed in ref. 1, but has the additional advantage of being immune to spin mixing effects in the channel, spin flip by non-magnetic scatterers, and dilution of the modulation by ensemble averaging over the electron energy. All this has been achieved by eliminating the channel magnetic field. The fabrication of this device is no more difficult than fabricating the 1-d SPINFET of ref. 1; in fact, it may be somewhat simpler since we do not need a top gate (or back gate) to induce the Rashba effect. It is possible that this device may be easier to implement, and may be somewhat more robust than the device of ref. 1.

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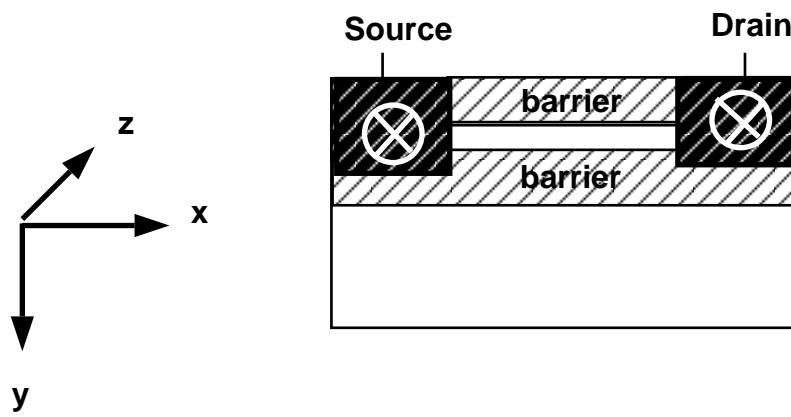
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Figure captions

Fig. 1: (a) Schematic of the spintronic modulator of ref. 1. (b) side view of the spintronic modulator proposed in this work, (b) top view showing the split gates.



(a)



(b)



(c)